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Development of Screen-Printed Breathing Rate Sensors

Abstract
This paper presents a method of screen-printing a conductive carbon nanotube printing paste onto textile substrates to prepare textronic strain sensors for measuring breathing rate. Screen-printed sensors can be integrated with garments after construction and do not require significant modification of the construction process. Personalisation of the garment is used to optimize sensor placement for improved measurement accuracy. Changes in the electrical resistance of the sensor as a result of changes in strain are detected and used to determine the breathing rate.

Key words: *textronics, textile sensor, breathing rate, carbon nanotubes, screen-printing.*

Introduction

Textronics can be used to create wireless, wearable systems to monitor physiological parameters in daily activities [1]. The breathing rate is an important physiological parameter that can be monitored [1 - 3] by measuring mechanical signal [4]. These low frequency mechanical signals are generated by movements of the human body while breathing and can be measured using strain gauges [1]. Commercial piezoelectric sensors can be used to ascertain the breathing rate [5, 6] and garments made with textronics can be used to distribute the sensors and electrodes optimally on the body [4]. Garments with sensors are designed to fit the body so that the garment is subjected to a moderate amount of pressure [7].

Textronic sensors can monitor vital signs, such as the breathing rate, without hindering comfort or performance. Precise sensor placement is important for monitoring physiological processes and personalised garment construction can ensure ideal sensor placement [4,8]. Textronic sensors that do not require special methods of garment construction are beneficial for sensor integration in garments.

This paper presents a sensor that is based on the detection of changes in resistance, due to changes in the dimensions of textiles (strain). Other sensors made with electrically conductive yarn incorporated directly into the fabric are currently implemented and detect a change in resistance, constructed [3]. One method of using this type of sensor is to insert a band that wraps around the chest incorporated into a textronic shirt [3]. Deformations of the human body while breathing subsequently cause a change in garment dimensions and a further change in resistance that is used to determine the breathing rate.

Sensors of this type, however, require the introduction of electrically conductive yarns into the garment's structure using insertion techniques (using weft or warp thread or sewing). The use of printing is advantageous in sensor construction because it does not require intervention in the knitting process, but instead can be applied to a finished shirt. Sensors can be printed using traditional printing techniques, such as screen-printing, as well as modern techniques, such as jet-printing. A previous work described a printed sensor for measuring the respiratory rate made in the form of a belt surrounding the chest [12].

Current printing with conductive inks has been used to create electric circuits on a textile surface, and techniques from this approach can be utilised to print an elongation strain sensor. Direct printing is one method of printing conductive ink whereby a mask is used to cover areas that are not to be printed [8]. Screen-printing is one type of direct printing that has been utilised on materials such as nonwovens [9]. Another method to apply a conductive circuit is to use ink jet printing to apply the conductive ink [10]. Most conductive inks contain metallic nanoparticles, but carbon nanotubes in an aqueous dispersion can also be used [11, 12].

By incorporating electronic functions into traditional textiles, increased functionality is possible. Textronics allow physiological signal monitoring during everyday activity, using wireless and wearable systems [1]. Functional materials allow the creation of garments with distributed sensors and electrodes [4]. Textronic systems must be able to sense, as well as pre-process, transmit, process and manage data [1]. Smart fabrics can act as flexible circuit boards, with sensors that record electronic signals and send them to a base station (via conductive pathways) for processing [1].

To build a correct system to measure the frequency of breathing, it is necessary to prepare a measuring sensor, equipment that processes the signal, and a monitoring system that converts the signal collected into readable information. The possibility to send the information via an antenna to part of the monitoring system exists for each of the systems studied. A truly intelligent material would allow sensing and processing while providing instantaneous feedback to the user [16]. In addition to electronic functionality, the textile must be wearable with a high degree of comfort. To maintain comfort, it is important that the measuring devices are of a small size [15].

The authors of this paper focused only on the first stage of such a system: a sensor devoted to determining changes in resistance related to breathing, which can be assesed per unit of time.

Methodology

A specially prepared printing paste doped with carbon nanotubes, investigated in a previous work, was used to screen-print ready-made shirts [12]. As breathing occurs, the garment changes in dimension, which causes variations in the resistance measured for further calculating the breathing rate.

Table 1 shows two substrate materials used to manufacture the shirts, that were screen-printed. The textile substrates were selected based on preliminary studies that assessed their effectiveness for athletic shirts.

The screen-printing procedure developed in a previous work was followed [12]. A carbon nanotube paste containing 55.8 ml of aqueous carbon nanotube dispersion (AquaCyl AQ0101, Nanocylcompany), 6.25 ml aliphatic urethane acrylate (Ebecryl2002), and 0.45 ml photoinitiator (Esacure DP250) was mixed.

Table 1. *Textile substrate properties;* 1. PES (Polyester), PU (Polyurethane), PA (Polyamide).

Name	Fibre content[1]	Structure	Mass per unit area, g/m^2	Thickness, mm	Apparent density, kg/m^3
Shirt A	81 % PES 19 % PU	warp knit	205	0.49	418.37
Shirt B	64% PA 36% elastane	warp knit with weft insertion	245	0.41	597.56

The nanotube dispersion was 90% pure with a carbon nanotube molecular weight of 0.5 - 1.5%. The average nanotube length was 1.5 μm with a diameter of 9.5 nm. The solution was thoroughly mixed, and excess water was removed by gravity drainage through filter paper for approximately 10 minutes. A squeegee and printing screen were used to apply printing paste to the fabric material of the personalised shirts. After printing, the materials were put in a 30 °C heat chamber and then placed under UV light with a dosage of 3.5 J/cm^2 for cross-linking.

Specimens were prepared for preliminary tensile testing by cutting 6 cm × 55 cm strips from the textile substrate materials, with each containing a 20 cm length screen-printed band. Electrodes were hand sewn using silver conductive yarn (Polyamide yarn X-Static (34 filaments coated with a layer of 15% Ag), with each filament mass doubled and sewn in two straight lines 4.5 cm apart. An Instron Model 5944 tensile tester was used to cyclically load the sensor for five cycles at each of the following strains: 1.25, 2.5, 5, 7.5, and 10%. The electrodes of the sample were connected to a Keithley Model 2000 digital multimeter to measure the resistance during strain testing.

The main goal of the research performed was determining the sensors sensitivity to mechanical deformations. The kinetics of the change in surface resistance under the influence of the action in stress used was recorded with the use of the Keithley multimeter.

Constant conditions of conditioning and researching the sample were maintained: a temperature of 23 °C, RH = 65% [12].

To fabricate personalised shirts from each substrate material, a test subject was scanned using a Model NX-16 [TC]^2 body scanner to determine their measurements. Due to technological limitations, the body scan was not used to generate a custom pattern; however, the bust measurement from the body scan was used to determine the size required in a standard shirt pattern. A shirt was then sewn from each substrate material. The test subject modelled the shirts for custom tailoring to personalise the garment fit. While modelling each shirt, the sensor location desired was marked for preparation of screen-printing. Two 5 cm × 5 cm sensors were printed on each shirt. One sensor was applied along the bust line, while the other was placed under the bust line, as illustrated in ***Figure 1***. Silver conductive thread (doubled) was sewn in two different configurations in order to create

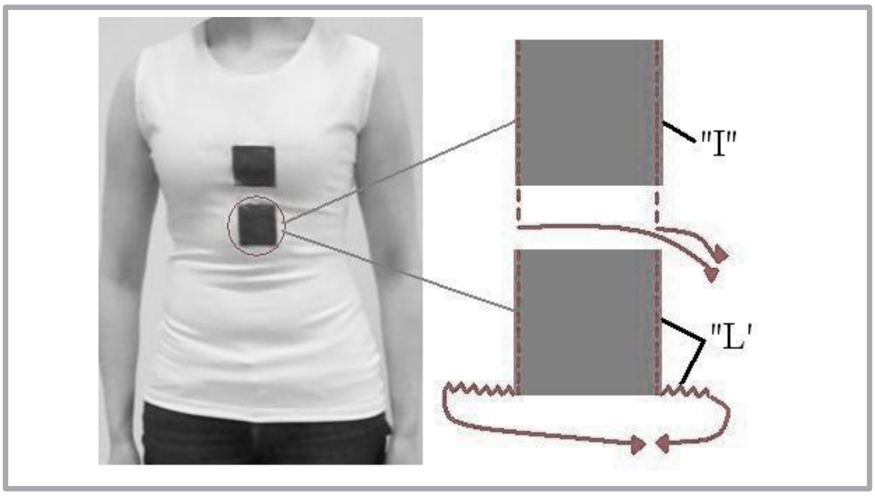

Figure 2. *Conductive wire configuration.*

the connections. The "I" configuration consists of two parallel lines of stitches, while the "L" configuration has two parallel lines of stitches and a zigzag stitch extending out from the sensor, as illustrated in ***Figure 1***.

Measurements were conducted with the subject in a seated position, which is not typical for most situations where breathing rate measurements are required, but is practical for the purposes of preliminary research. Electrical connections to the Keithley multimeter and corresponding lap top computer necessitated the positioning of the subject in a sedentary state. The resistances recorded were analysed using the msProcess package in the statistical analysis program. The breathing rate was determined based on the number of local resistance minima detected. For comparison, the breathing rate was manually determined by counting the number of inhalations over five minutes.

Hysteresis properties of the textile substrate materials were determined with the tensile tester by subjecting a 5 cm × 5 cm sample to ten cycles of 20% strain along the wale direction, based on previous work. The pressure of the garment on the subject tested, which related to the garment fit and elastic properties of the textiles used, was calculated based on the body and garment dimensions and measurements. The force versus strain was plotted for the relaxation portion of the final strain cycle, and the relationship between the force and strain determined by curve fitting. The Laplace formula, (***Equation 1***), was used to determine the garment pressure during wearing.

$$P = \frac{2\pi F}{G_1 W} \qquad (1)$$

where:
F – force in the knitted fabric strip of width W, in cN;
G_1 – circumference of the body part (or cylinder), in cm; and
W – width of the knitted fabric strip, in cm.

The effect of laundering on the ink property is an important consideration and can be determined by comparing initial measurements with those after several cycles of washing [13].

To assess the washability of the screen-printed strain sensor, the garments were subjected to one washing cycle of 40 °C for 30 minutes according to Standard PN EN ISO 105-C06:2010. The garments were hung to dry in ambient conditions (20 °C and 65% relative humidity). Previous research indicated that for up to 20 cycles of washing, the conductivity decrease observed was not significant enough to affect the maximum or minimum peak measurements recorded [12].

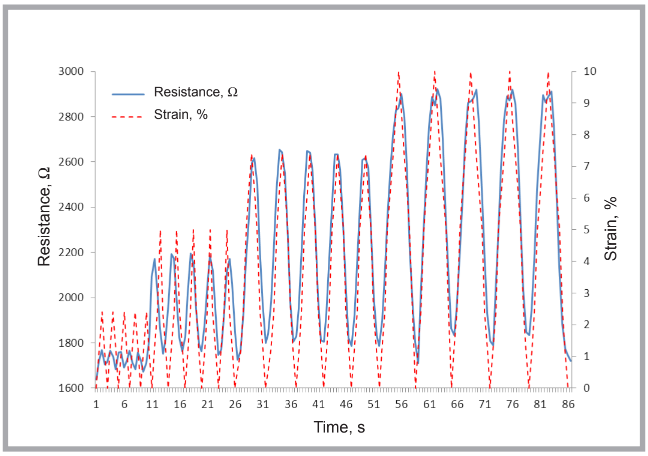

Figure 2. *Sensor resistance and strain versus time – Shirt A.*

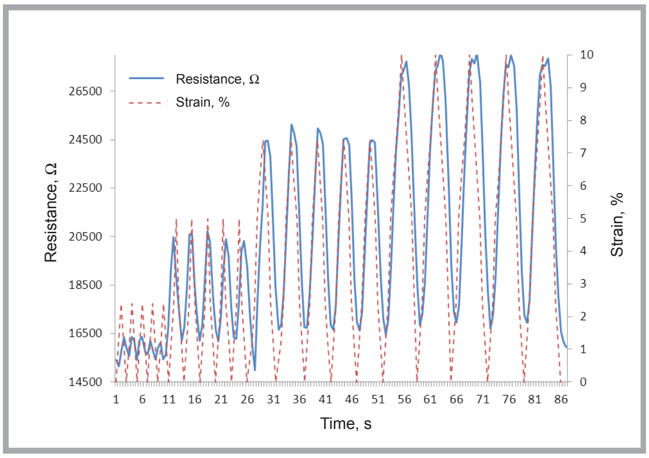

Figure 3. *Sensor resistance and strain versus time – Shirt B.*

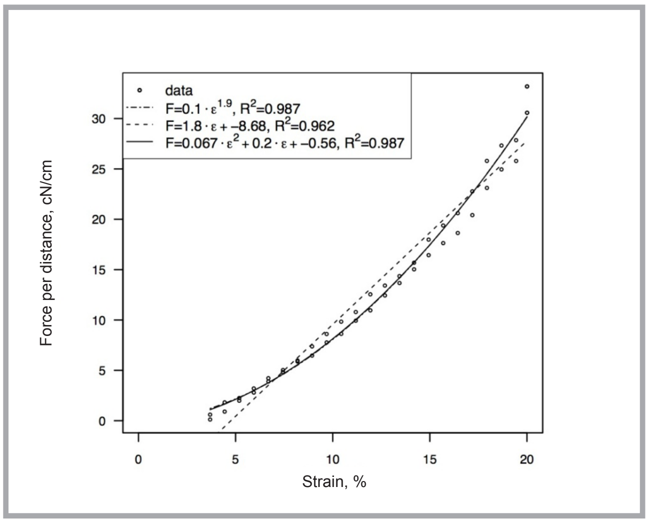

Figure 4. *Force versus strain, Shirt A.*

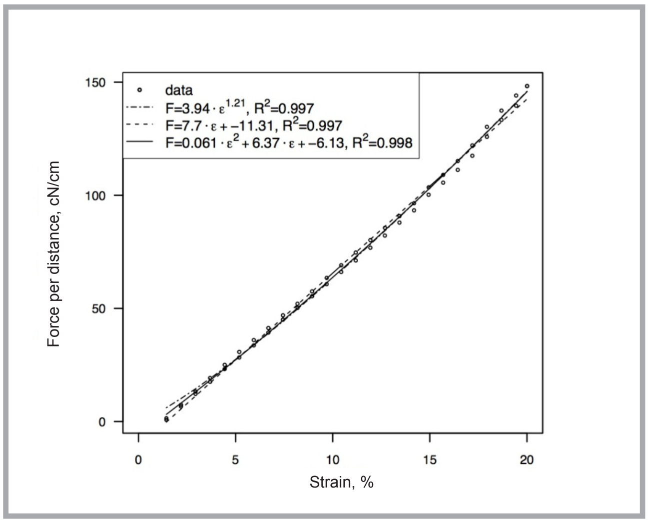

Figure 5. *Force versus strain, Shirt B.*

Table 2. Personalised shirt pressures.

Location	Pressure, hPa	
	Shirt A	Shirt B
Bust	8.75	7.03
Underbust	4.11	5.60

Table 3. Breathing rate determined from screen-printed sensors.

	Breathing rate, breaths per minute							
	Shirt A				Shirt B			
	Bust		Underbust		Bust		Underbust	
	I	L	I	L	I	L	I	L
Mean	9.5	12.5	13.6	13.1	11.9	13.1	10.7	14.6
Standard Deviation	0.71	3.16	2.18	1.60	1.29	1.05	1.37	0.80
Coefficient of Variance	0.07	0.25	0.16	0.12	0.11	0.08	0.13	0.05

Results and discussion

There was no noticeable difference in the application of printing paste and finished products for shirts A and B. A different application method, such as direct printing, may reduce the amount of excess dyestuff present on the final product.

Plots of the sensor resistance and strain over time examined using the tensile tester for Shirts A & B can be seen in ***Figures 2*** and ***3***. An Instron tensile tester was used, with the distance between clamps of 45 cm, and the constant rate of movement of 2 mm/min. Even at low strains, the change in sensor resistance with varying strain was sufficiently large to count the minima using a detection algorithm, while higher strains resulted in larger, easier-to-detect changes in resistance. The magnitude of resistance measured is dependent on the textile material.

The pressure of the garment on the wearer influences sensor accuracy, hence the pressure of the garments used was determined. ***Figures 4*** and ***5*** show the relationship between force and strain, as well as curves of best fit for the different textile substrates. The garment and body measurements, as well as the quadratic relationship between force and strain, were used to determine the force for the Laplace equation. Using the Laplace equation, pressures at the bust and underbust placements were calculated, shown in ***Table 2***. The higher pressure of Shirt A at the bust may account for the more accurate breathing rate measurements, but further experimentation is also needed.

The graphs were completed after the fifth measurement cycle. Based on the graphical analysis performed, we can see that a quadratic equation is the most accurate representation of the data experimentally obtained for Shirts A and B. The coefficient of determination, R^2, shown for each of the fit curves indicates the goodness of fit, with the highest degree of fit for R^2 close to one. The force, in cN/cm, corresponding to a given strain in % can be calculated with known validity for strains below 20% using a quadratic equation, and the coefficients determined were based on test work. Strains above 20% can be used, but there is uncertainty about the force obtained above this level.

Using the final measurements of the garments, the body measurements obtained with the body scan, and the force equation determined via hysteresis testing, the pressure exerted by the garment on the body was calculated. As the garments were constructed so that breathing strains the fabric in a direction perpendicular to the columns of knit stitches, the force equations determined by stretching perpendicularly were used. The key garment measurements for the breathing rate sensor are those of the bust circumference and underbust circumference; the pressure force was calculated in these locations. Results of the calculations can be seen in ***Table 2***.

Representative plots of the resistance measured while breathing (for the "I" configuration of connections and bust sensor) can be seen in ***Figures 6*** and ***7***. ***Table 3*** shows the mean breathing rate and statistical analysis for the different sensor configurations. A seated person breathing normally at a rate of 10.6 breaths per minute was determined by observing and counting breaths. Comparing results presented in ***Figures 6*** and ***7*** especially with baseline values, we can see that the "I" sensor configuration provides more accurate results than the "L" sensor configuration. Shirt A indicates no significant difference in measurement efficacy between the bust and underbust sensors, while Shirt B shows more accurate results for the bust sensor.

The slight drift in measurements observed in ***Figure 7*** may be attributed to the movement of the shirt relative to the subject's body. This movement and re-

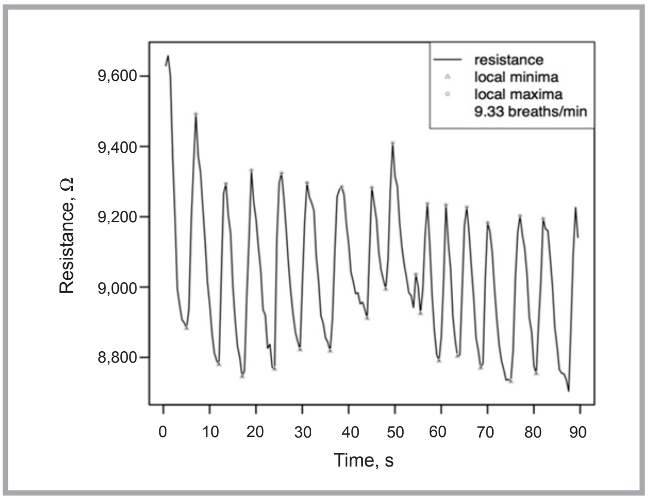

Figure 6. *Resistance when breathing, Shirt A, Bust configuration "L".*

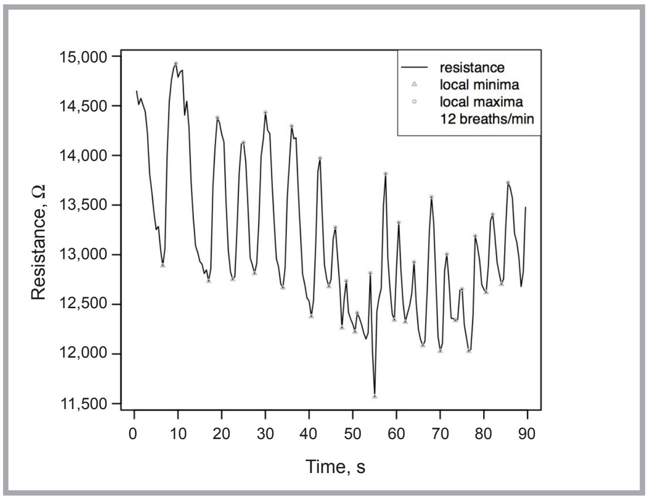

Figure 7. *Resistance when breathing, Shirt B, Bust configuration "L".*

lated variation in resistance magnitude do not have an impact on the breathing rate determined as only the number of peaks is used in the calculation and not the magnitude.

Preliminary work carried out at the **Department of Material and Commodity Sciences and Textile Metrology** indicated, according to our assumptions that the sensor resistance varies with temperature and humidity changes. However, this should not have a significant impact on the final measuring effect, which depends on the counting of resistance pulses and not the level of the resistance value. Nevertheless in future investigations the boundary limits should be determined depending on the threshold of the future counting system.

Future work

In sporting applications, considerable laundering is required as the garments are exposed to large amounts of sweat. Further testing to determine the suitability of the printing paste with additional laundering cycles, as well as resistance to perspiration, is required. Other printing techniques could also be explored to improve the tactile feel of the screen-printed sensor, increase aesthetics, and optimise print paste delivery. A quite different problem is the designing of the whole textronic system, which means counting, monitoring and eventual transmitting of the breathing rate signal.

Conclusions

To obtain a personalised garment that fits snugly without being uncomfortably tight, pressure calculations based on the Laplace equation are useful. We can see that the pressure varies based on the segment of the body that is examined, due to the changing circumference. As the pressures calculated for all of the sample garments are less than 10 hPa, we can see that those obtained are comfortable. Clothing elongations greater than 5% observed indicate that the garments fit closely to the body, as required for a breathing rate sensor.

Sample A poses better efficiency of detection of the breathing rate, which is comparable to real breathing, than sample B. Moreover a better relation between the measurement and real breathing was obtained for sensors located at the bust. Pressure calculated on the basis of the Laplace equation from data obtained using sensors on shirt A is higher than that calculated using data from sensors on shirt B. It was also observed that in the case of both shirts, pressure obtained from the Laplace equation on the basis of results registered by sensors on the bust are higher than the same pressure calculated from sensors located at the underbust.

Screen-printing with conductive paste is an effective method of applying a strain sensor to a garment manufactured using standard techniques. However, it is necessary to carry out further work to refine the composition of printing paste and the method of application for printing. Changes in conductivity and sensitivity observed do not cause significant changes in breathing rate measurement, an important factor for garments. Screen-printed strain sensors for measuring the breathing rate show promise for monitoring physiological signals.

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